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ON THE VARIATIONS OF THE COSMIC-RAY INTENSITY ASSOCIATED WITH THE MAGNETIC STORM

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§ 1. Introduction.

It has been reported by several investigators that the intensity of cosmic-ray decreases at the time of the main phase of the magnetic storms.[1~4] They have been attempted to study the correlations between the variations of the cosmic-ray intensity and that of the magnetic storms, but there are no complete interpretations, up to the present. S. E. FORBUSH investigated on this problem by using the records of the observations of four stations at different latitudes and reported that variations in cosmic-ray intensity during the magnetic storms were world-wide, and there were few latitude-effects. Many of previous investigators attempted to take the correlations between the variations of the horizontal intensity of terrestrial magnetic field during the main phase of magnetic storms (ΔH) and those of the cosmic-ray intensity ($\Delta I/I$), but there are no good correlation in general.[3] (Fig. 1) For example the amplitude of the variations of the horizontal intensity of the terrestrial magnetic field was very large during each storm of July 5, 1941 ($H=650\,\gamma$) and Sept. 18, 1941 ($H=417\,\gamma$), but there were no variations in the cosmic-ray intensty ; on the other hand, the amplitude of the magnetic storm at May 1, 1942 was not so large ($H=60\,\gamma$), but the variation of the cosmic-ray intensity was very large ($\Delta I/I=-(7\sim 9)$ %). J. CLAY and E. M. BRUINS[4] reported that the effect of the magnetic storm on the intensity of the cosmic-

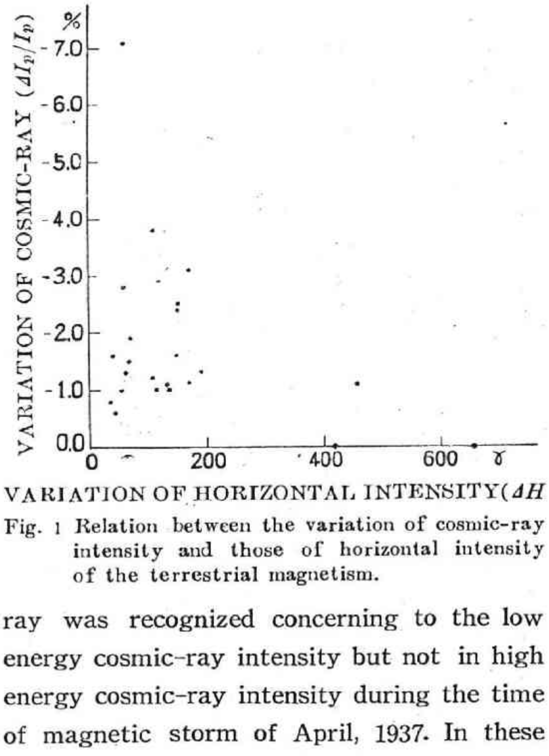

Fig. 1 Relation between the variation of cosmic-ray intensity and those of horizontal intensity of the terrestrial magnetism.

ray was recognized concerning to the low energy cosmic-ray intensity but not in high energy cosmic-ray intensity during the time of magnetic storm of April, 1937. In these case, it is considered that the amplitude of the variations of the intensity of the cosmic-ray depends on the radius and the intensity of the equatorial ring-current at the time of magnetic storm as was investigated by BIRKELAND and STÖRMER. One of writers (T.K.), and others[5] suggested that these different types occurred due to the different radius

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of the equatorial ring-currents at the time of the magnetic storms. One of the writers (Y.K.),[6,7] applying his new theory of the magnetic storm, showed the relation between $\Delta I/I$ and $\Delta H/v^{\frac{3}{2}}$ (where v is the velociy of the particle in the equatorial ring-current) that is the relation between $\Delta I/I$ and the magnetic moment of the magnetic field due to the equatorial ring-current, and attempted to interpret the mechanism of the effect of the magnetic storm on the cosmic-ray intensity. Y. SEKIDO[8] showed that the variation of the terrestrial magnetism could be separated to two parts, that is the one was owing to the equatorial ring-current and the other owing to the ionospheric disturbance according to the variation of the cosmic-ray intensity. F. EVANCE[9] showed that the variation of the terrestrial magnetism was occurred by the variation of the cosmic-ray intensity, and that these values were the same order to experimental ones. S. E. FORBUSH [10] discovered several cases of a sudden increase in the cosmic-ray intensity before the magnetic storm. H. V. NEHER and W. C. ROESCH[11] attempted to interpret their increases to be owing to the particles emitted from the sun at the point of view that they were associated with solar flares. Recently H. ALFVÉN[12] attempted to interpret them by his magneto-hydrodynamic wave. Y. SEKIDO[13] reported that the cosmic-ray intensity increased extraodinarily at thirty hours before magnetic storms. Y. MIYAZAKI and others[14] reported that the decrease of the cosmic-ray intensity occurred before the occurrence of the magnetic storm when the magnetic storm begun without the sudden commencement. Recently S. HAYAKAWA and others[15] explained that the maximum variation of cosmic-ray intensity occurred after the main phase of the magnetic storm as the radius of the ring-current expands with time. In either case, however, they could not illustrate sufficiently the variations of cosmic-ray intensity associated with the magnetic storm. Now we will attempt to take the correlation between the variation of the cosmic-ray intensity and the radius of the equatorial ring-current at the time of magnetic storm by using the new theory of one of writers (Y.K.).

§ 2.

According to the previous paper of one of writers (Y.K.),[7] we may assume as follows:

1) The variation of cosmic-ray intensity associated with the magnetic storm is due to the variation owing to the magnetic field of the equatorial ring-current.

2) The equatorial ring-current is produced by charged particles from the sun, and their velocities are determined by the time difference between the sudden commencement and the main phase of the magnetic storm.

3) Charged particles in the equatorial ring-current move with the same velocity by which is emitted from the sun.

As the radius of this equatorial ring-current (ρ) is obtained by making the centrifugal force of particles at that position and the deviating force owing to the terrestrial magnetic field be equal, we have

$$\frac{mv^2}{\rho}=evH,$$

therefore

$$H\rho=\frac{m}{e}v,$$

where m, e is the mass and the charge of these particles, respectively, and H, the horizontal intensity of the terrestrial magnetic field at that position, and v those velocities.

Let the magnitic moment of the terrestrial magnetic field be M, then we have

$$\frac{M}{\rho^2}=\frac{m}{e}v,$$

therefore

$$\rho^2=M\cdot\frac{e}{m}\cdot\frac{1}{v}. \qquad \cdots\cdots\cdots\cdots\cdots(1)$$

Next, let the current intensity of the equatorial ring-current be i, then the magnetic moment of the magnetic field due to the equatorial ring-current (ΔM) may be given as follows:

$$\Delta M=\pi\rho^2 i$$

$$=\pi\cdot M\cdot\frac{e}{m}\cdot\frac{1}{v}\cdot i,$$

therefore

$$\frac{\Delta M}{M}=\pi\cdot\frac{e}{m}\cdot i\cdot\frac{1}{v}. \qquad \cdots\cdots\cdots\cdots\cdots(2)$$

§ 3. Data Used in This Report.

Data of the earth's magnetic field used here were obtained from the record of the Kakioka Magnetic Observatory, Kakioka, (36°14′N,140° 11′E), the Geophysical Institute of Tôhoku Univetrsity, Sendai (38° 15′N, 140° 52′ E) and the Onagawa Magnetic Observatory of Tôhoku University, Onagawa, near Sendai (38° 26′ N, 141° 28′ E), being distinguished with the sign of H_k, H_s, H_o, respectively. On the data of the cosmic-ray intensity, we used the observed values of the Nishina Laboratory, Scientific Research Institute, Tokyo (35° 45′ N, 139° 43′ E), and of Cosmic-ray Laboratory of Nagoya University, Nagoya (35° 10′ N, 136° 58′ E), which were excluded the barometric effect, and their comparisons were done with the data reduced to those of the Counter Telescope No. 1 of the former (total intensity, ±40°), according to Y. SEKIDO[13].

§ 4. Results Obtained and Discussion.

The values obtained from the above data are shown in Table 1.

As ρ is determind by v according to the assumption mentioned in § 2, we obtain the relation of $\Delta I_p/I_p$ and v instead of ρ, which is shown in Fig. 2. This is rectangular hyperbola relation. Therefore, if we took the relation of $\Delta I_p/I_p$ and $1/v$ as shown in Table 2 or Fig. 3 it becomes almost linear relation.

The correlation coefficient between $\Delta I_p/I_p$ and $1/v$ is

Table 1.

No.	Date				t^* (sec)	v (10^8cm/sec)	$\Delta I_p/I_p$ (%)
1	Jan.	25,	1938	H_s	22700	6.59	−2.5
2	〃	22,	〃	〃	25700	5.82	−3.1
3	Mar.	24,	1940	〃	7460	20.1	−1.1
4	〃	30,	〃	〃	12300	12.2	−1.0
5	Des.	16,	1944	〃	32600	4.59	−2.9
6	Aug.	22,	1947	H_k	5210	28.8	−1.3
7	Sep.	12,	〃	〃	2780	53.9	−0.7
8	〃	23,	〃	〃	5120	29.3	−1.3
9	Nov.	9,	〃	〃	8700	17.4	−1.1
10	Sep.	23,	1948	〃	3980	37.7	−1.0
11	Oct.	1,	〃	〃	15560	9.64	−3.8
12	〃	13,	〃	H_o	45080	3.32	−1.6
13	Dec.	21,	〃	〃	7520	20.0	−1.0
14	〃	24,	〃	〃	6260	24.0	−1.5
15	〃	30,	〃	〃	9500	15.8	−0.6
16	〃	31,	〃	〃	8420	17.7	−1.2
17	Mar.	1,	1949	〃	4400	34.1	−1.3
18	Apr.	30,	〃	〃	9860	15.4	−0.8
19	May.	4,	〃	〃	12980	11.6	−1.9

$t^* = t_{Mh} - t_{sc} + 500$

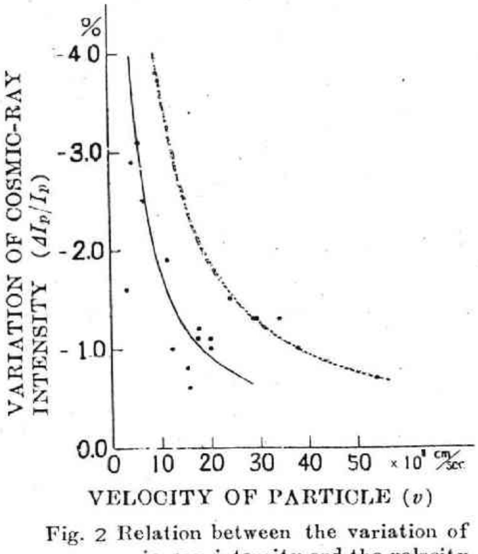

Fig. 2 Relation between the variation of cosmic-ray intensity and the velocity of the particle from the sun. The full line represents a mean line.

$$r=0.64, \qquad (3)$$

and that is a moderate correlation between them.

According to (2),

$$\frac{\Delta M}{M} \backsim \frac{1}{v},$$

therefore

$$\Delta I_p/I_p \backsim \Delta M/M.$$

$\Delta M/M$ is the rate of variation of magnetic moment of the terrestrial magnetic field during the magnetic storm.

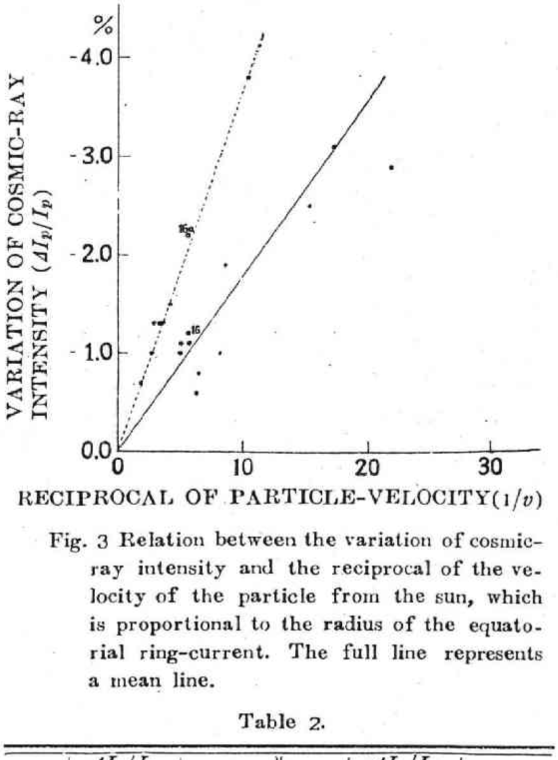

Fig. 3 Relation between the variation of cosmic-ray intensity and the reciprocal of the velocity of the particle from the sun, which is proportional to the radius of the equatorial ring-current. The full line represents a mean line.

Table 2.

No.	$\Delta I_p/I_p$ (%)	$1/v$	No.	$\Delta I_p/I_p$ (%)	$1/v$
1	−2.5	15.2	11	−3.8	10.4
2	−3.1	17.2	12	−1.6	30.1
3	−1.1	5.0	13	−1.0	5.0
4	−1.0	8.2	14	−1.5	4.2
5	−2.9	21.8	15	−0.6	6.3
6	−1.3	3.5	16	−1.2	5.6
7	−0.7	1.9	17	−1.3	2.9
8	−1.3	3.4	18	−0.8	6.5
9	−1.1	5.7	19	−1.9	8.6
10	−1.0	2.7			

From the equation, $\rho^2 \backsim \frac{1}{v}$, we have

$$\Delta I_p/I_p \backsim \rho^2.$$

Therefore, if the radius of the equatorial ring-current is small, $\Delta I_p/I_p$ will be also small, and the larger its radius becomes, the larger $\Delta I_p/I_p$ becomes with proportion of square of its radius.

It seems to be caused by the following reasons that the correlation coefficient which was calculated in (3) is not high enough, that is:

i) In this paper we assume that the current intensity (i) of the equatorial ring-current is constant but it will not be always constant.

ii) The equatorial ring-current, which affects the decrease of the cosmic-ray intensity, does not always agree with that which is determined by the assuption (2) in § 2.

However, the linear distribution in Fig. 3 seems to suggest that the current density of the equatorial ring-current has the sharp distribution of some particular value.

In Fig. 3, seven points (Nos. 6, 7, 8, 10, 11, 14, 17) are almost laid on the straight line (dotted line). In these cases the time of the maximum decrease of the cosmic-ray intensity is behind to that of the maximum decrease of horizontal intensity of earth's magnetic field. This fact shows that the velocity of the particles is large in earlier stage of the magnetic storm and becomes smaller in its last stage, which affect the maximum decrease of the cosmic-ray intensity. Therefore, it will be consider that this straight dotted line must incline more and more to the mean straight line.

For example, on the case of No. 16, the cosmic-ray intensity decreases on two steps as shown in Fig. 4. Using the value of the first step (point A), we obtain the point of sign 16 in Fig. 3, and by the second step (point B), we obtain the point of 16 a in the same figure. These can well be explained by considering that the radius of the equatorial ring-current changes afterward.

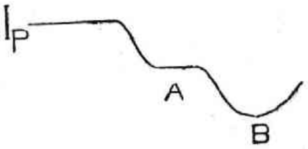

Fig. 4. A special case that the cosmic-ray intensity changes on two steps.

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